

How high in pT does “soft” physics play a role?

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- **Implications of the opaque parton plasma at RHIC**

Recall charge to RHIC-II working groups:

...

#2 How does the clearly evident thermodynamic character of a high-energy heavy-ion collision evolve from the zero entropy initial state? How does the collision thermalize so quickly?

#3 What are the properties of the strongly-coupled quark-gluon plasma? Transport properties? Medium properties? Resonant states? Collision probability? Screening length?

...

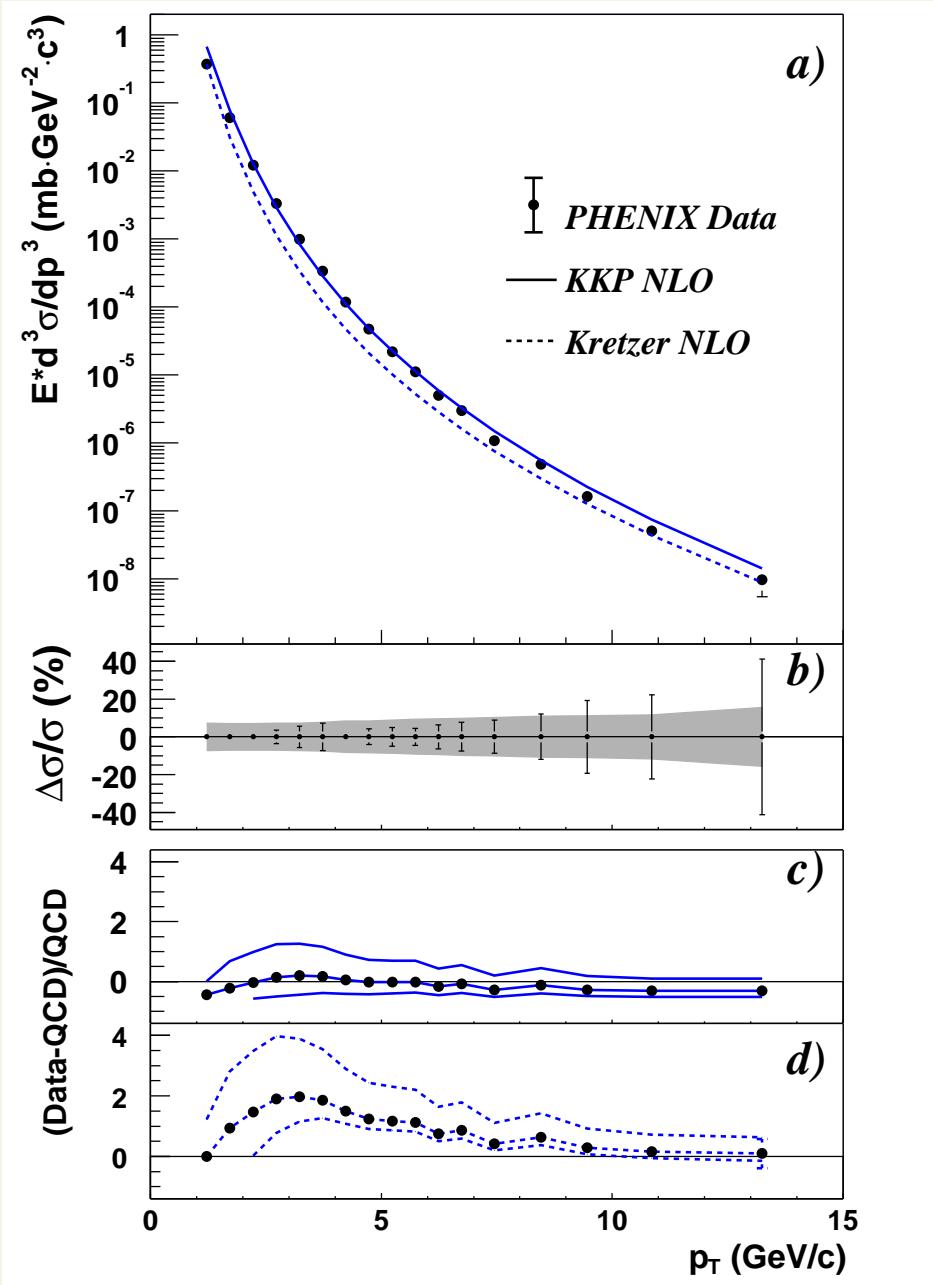
~ what kind of matter did we create, and how did it evolve?

→ what can high-pT measurements tell us about these?

What is "soft", what is "hard"?

- wounded nucleon A^1 vs binary collision $A^{4/3}$ scaling?
- low-pT vs high-pT?

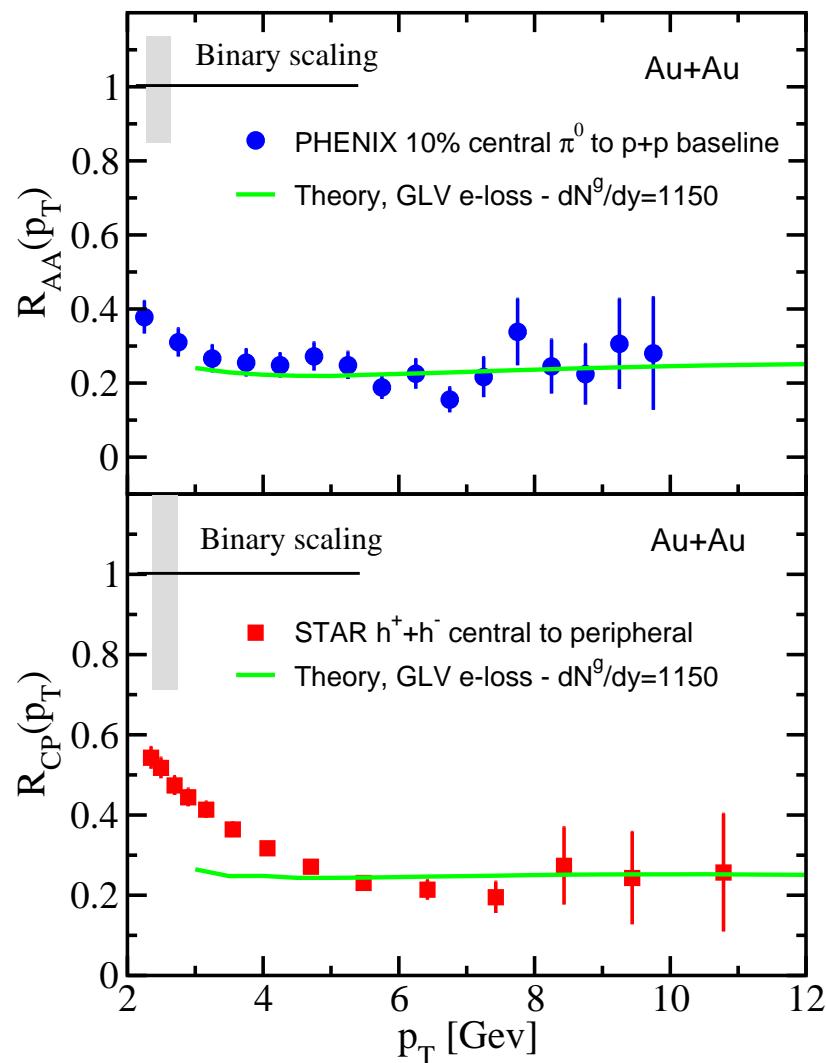
HERE: hard \Leftrightarrow pQCD (w/ energy loss, Cronin,...) works
soft \sim "nonperturbative"



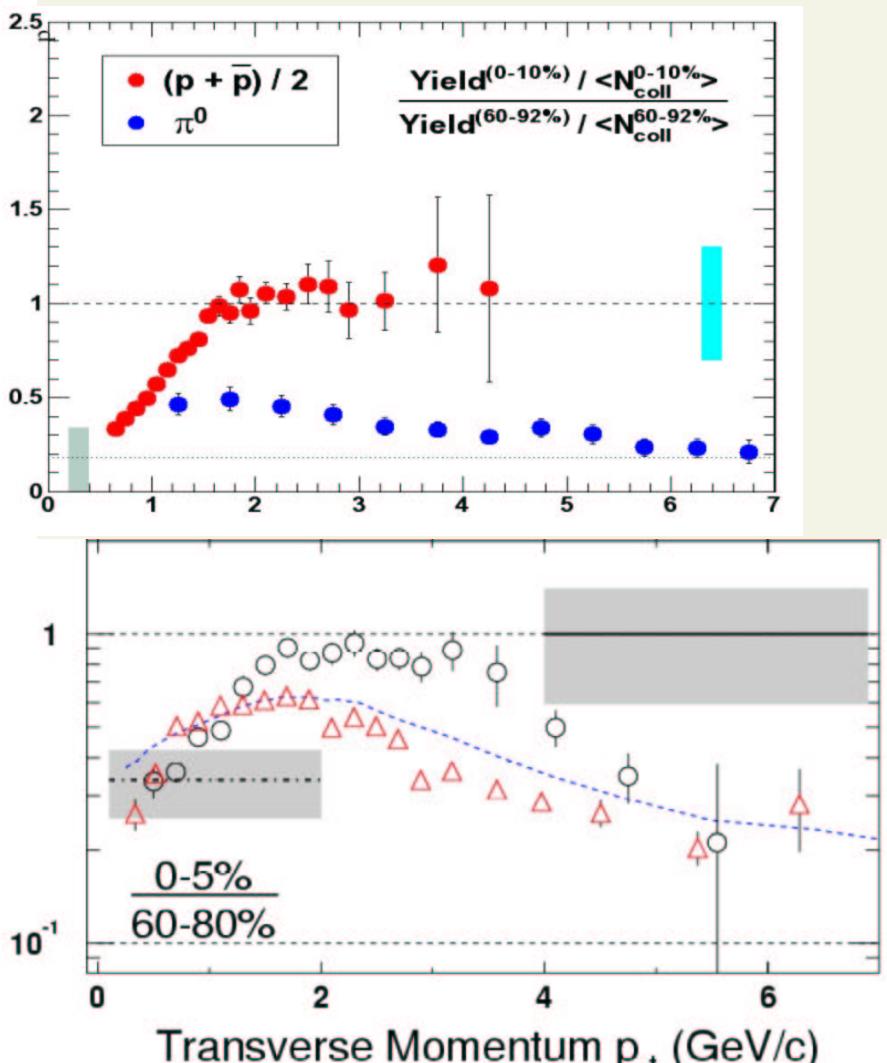
$$dN_h = f_{A,i} \otimes f_{A,j} \otimes d\sigma_{ij \rightarrow aX} \otimes D_{a \rightarrow h}$$

**p+p: NLO pQCD works well
above $p_T > 1 - 2$ GeV**

Au+Au: GLV quenching model vs STAR, PHENIX - Vitev '04



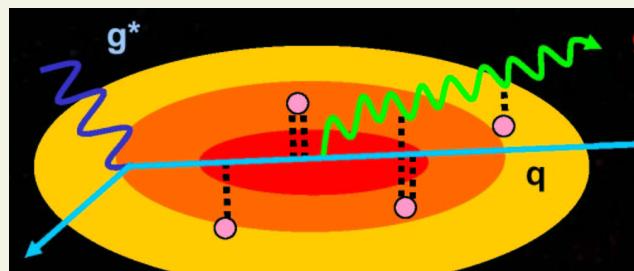
π : $pT > 3$ GeV, but h^\pm $pT > 5$ GeV



→ baryon anomaly

Need to know the medium

energy loss probes color charge density Wang, Gyulassy, Vitev, Wiedemann et al



GLV approach: static Yukawa scattering centers

$$V(q) \propto e^{-i\vec{x}\vec{q}} \delta(q^0) \frac{\alpha_s}{\vec{q}^2 + \mu_D^2} T_a^{jet} \times T_a^{center}$$

$$\sigma_{tot} \sim \alpha_s^2 / \mu_D^2, \quad \langle \Delta q^2 \rangle \sim \mu_D^2$$

need inputs: interactions, spacetime evolution

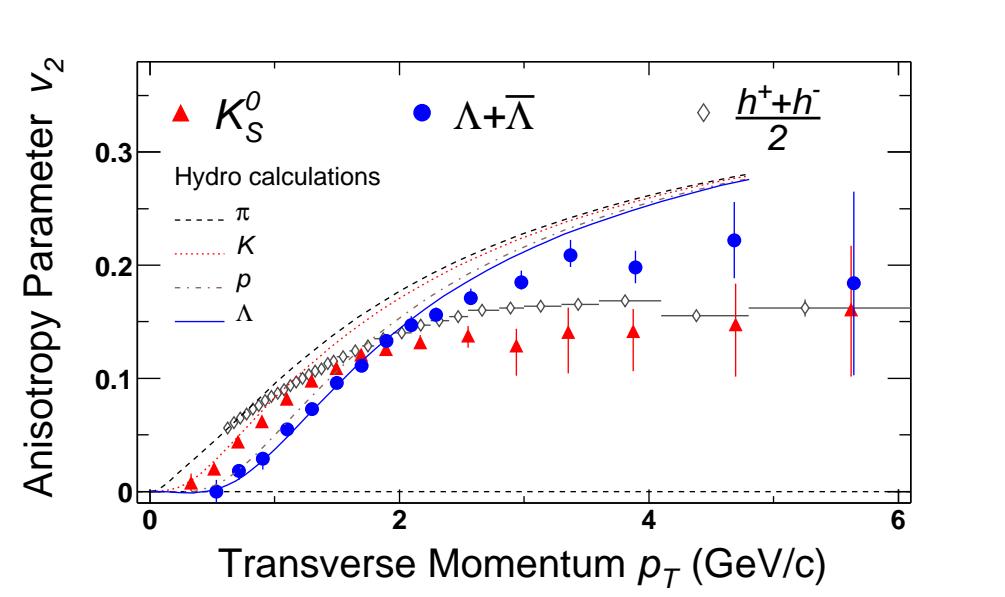
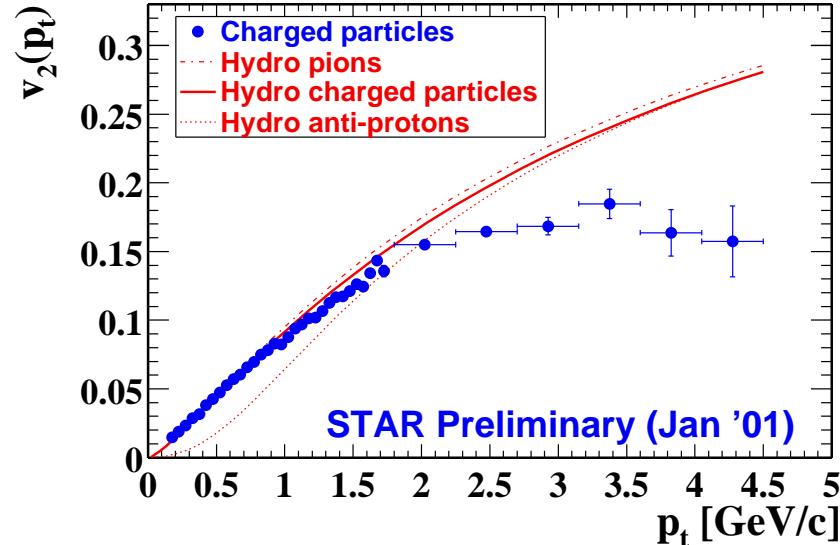
useful, approximate "pocket" formula:

$$\Delta E^{(1)} \approx const \times \alpha_s^3 \int \underbrace{dz}_{\textcolor{red}{dz}} \cdot \textcolor{red}{z} \cdot \rho(z, t = z/v) \quad dE/dx \propto x(!)$$

→ needs to be tested against realistic dynamical scenarios

RHIC: "consistent" $dN^{glue}/d\eta = 1150 \approx dN^{hadr}/d\eta \rightarrow$ but where are the quarks??

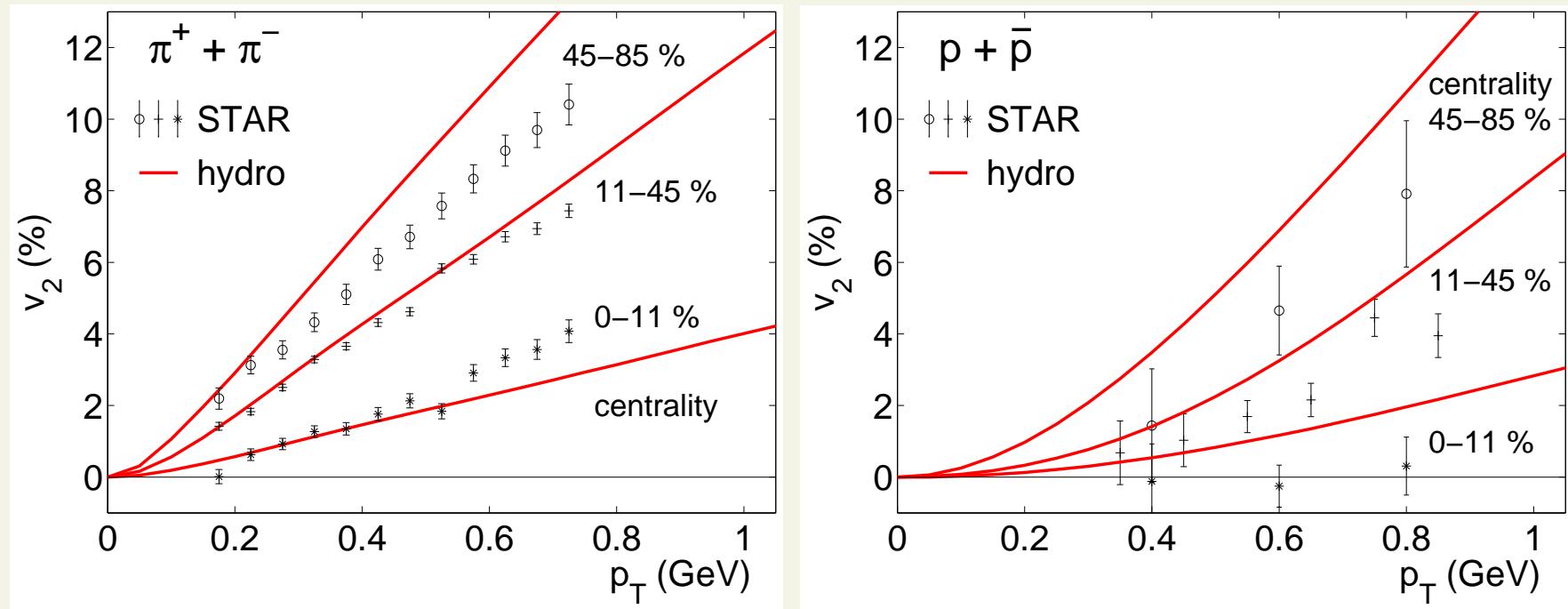
ideal hydrodynamics at RHIC Kolb, Heinz, Huovinen; also Hirano et al, ...



seems locally thermalized medium at low $pT < 2$ GeV
(spectra also work, even thermal parametrizations do...)

but on closer inspection (higher experimental resolution)

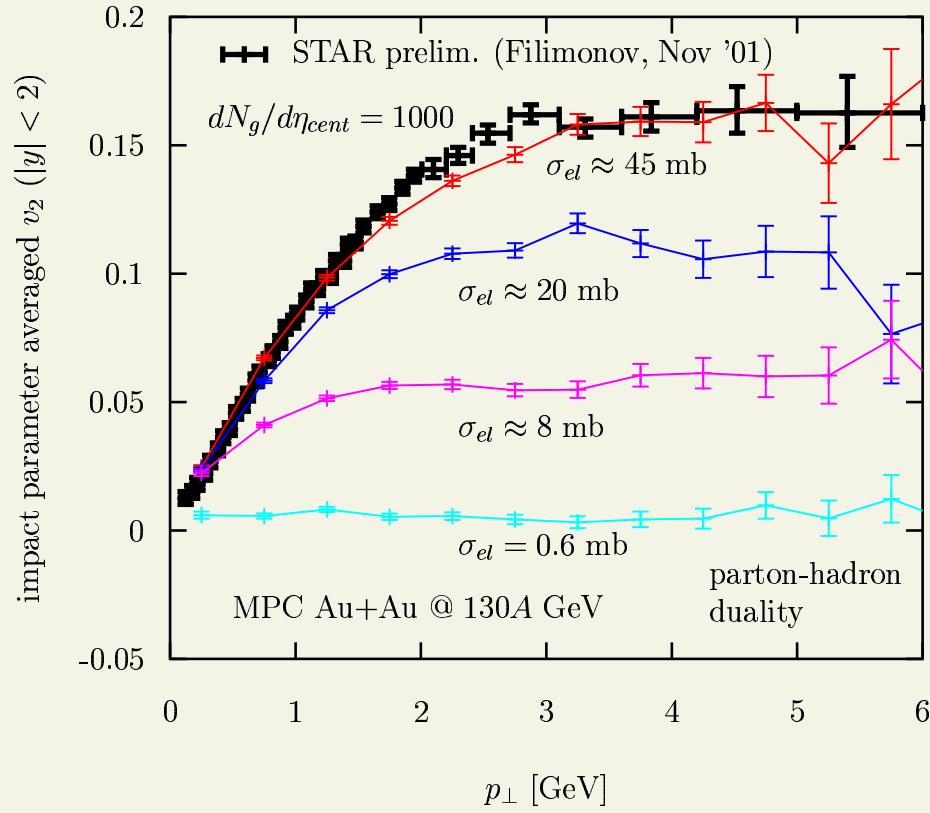
deviations even below $p_T < 1$ GeV(!)



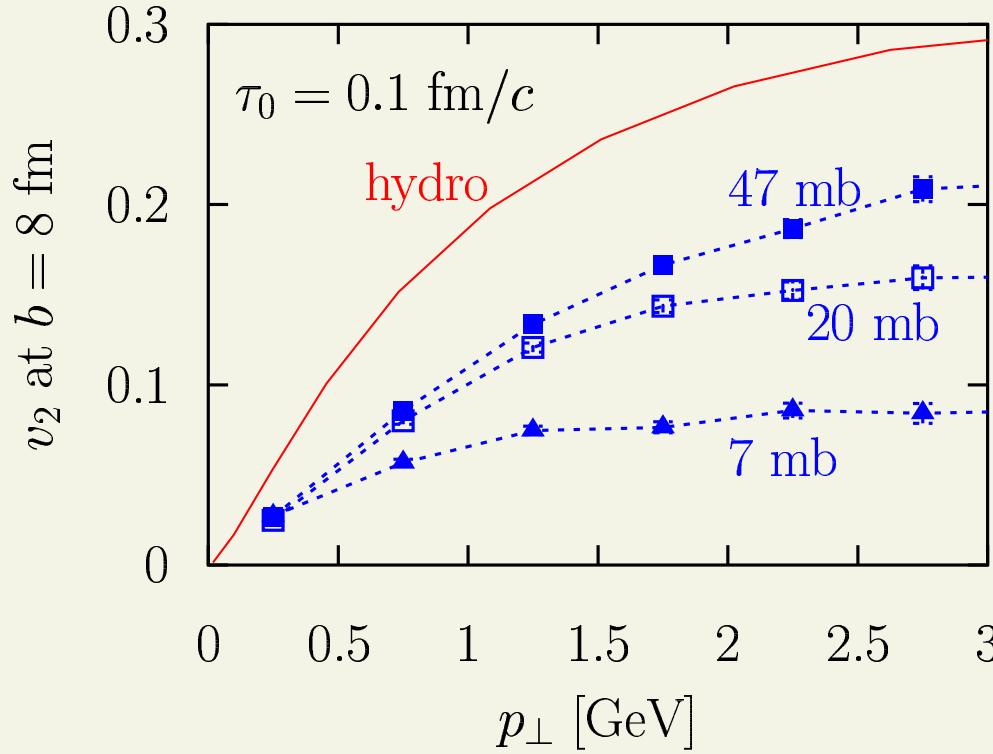
→ must find a better fit (EOS, initconds, freezeout) or else we need some new ingredients

nonzero mean free path ~ 0.1 fm \rightarrow causes dissipation

DM & Gyulassy '02:



DM & Huovinen, PRL94 ('05):



idealized dissip. (long wavelengths/timescales): viscosity \rightarrow viscous hydro

QM dictates nonzero viscosity: $\eta/s > 1/15$ (kinetic theory), $1/4\pi$ (AdS/CFT)

Two-component models: jets + soft medium

- medium affects jets: **high-pT suppression, momentum anisotropy, jet broadening, soft radiation, ...**
- jets influence medium: **collective excitations**

both cases: one-way energy/particle transfer, from high-pT to low-pT

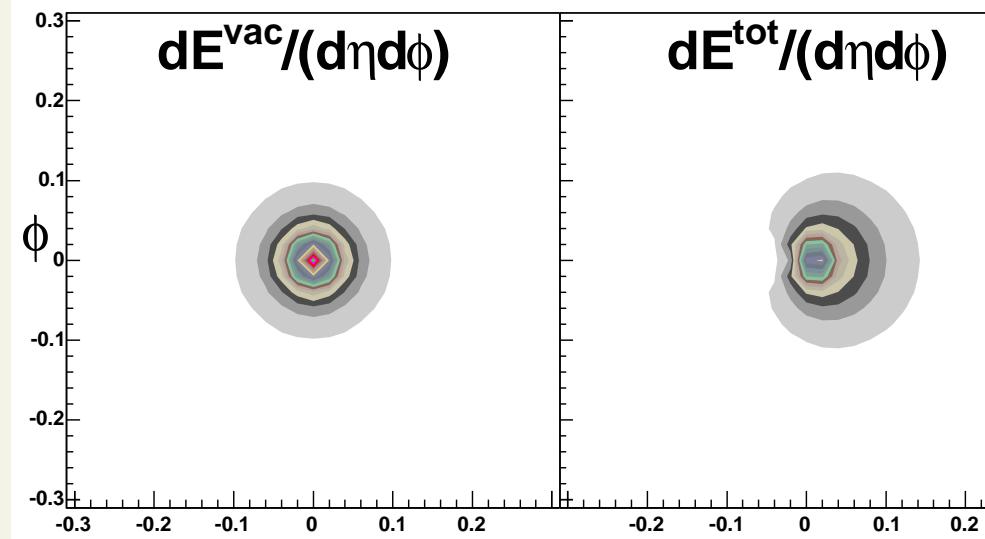
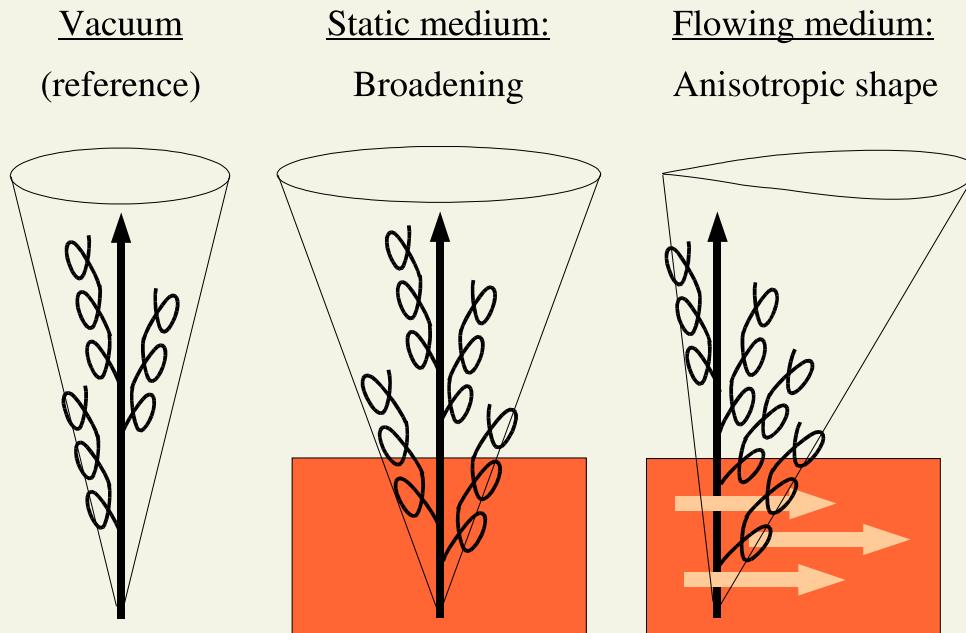
Bulk affects jets

Gyulassy, Vitev, Wang, et al; Wiedemann et al; Hirano & Nara; ...

tip of the iceberg - color charge density: R_{AA} , v_2 , jet correlations, ...

BUT even collective flow matters:

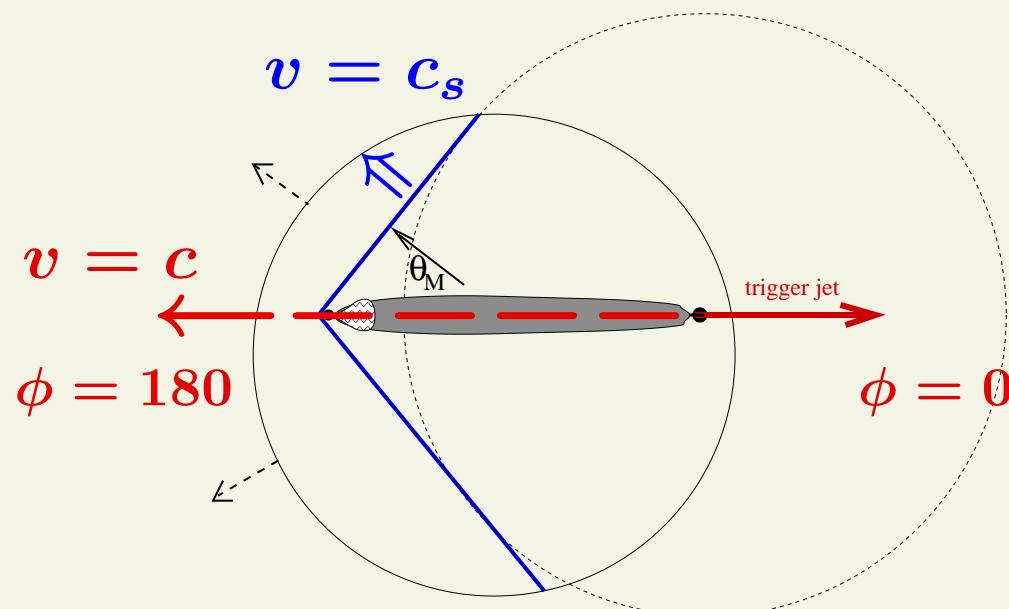
Armesto, Salgado, Wiedemann ('04) - **deformed $\eta - \phi$ jet cone**



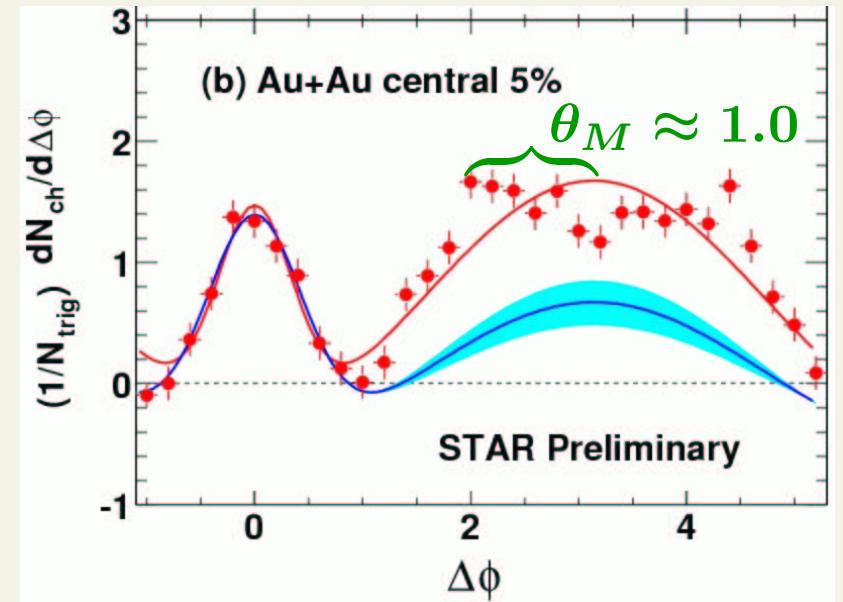
Jet-induced collective excitations?

Short-wavelength probe could generate collective hydrodynamic response
- exciting, *hotly debated*, possibility

“sonic boom” Stöcker '04, Casselderey-Solana et al



azimuthal correlations F. Wang [STAR] '04



$$\text{Mach cone: } \cos \theta_M = c_s/c \quad \Rightarrow \quad c_s^2 \approx 0.25 - 0.3 \cdot c^2 \dots$$

$$\text{ideal parton gas: } c_s^2 = c^2/3$$

**Jets & bulk are the QCD matter we have at hand -
separation is largely arbitrary**

- **need to treat both together \Rightarrow e.g., use covariant transport (MPC)**

Up-down migration in pT

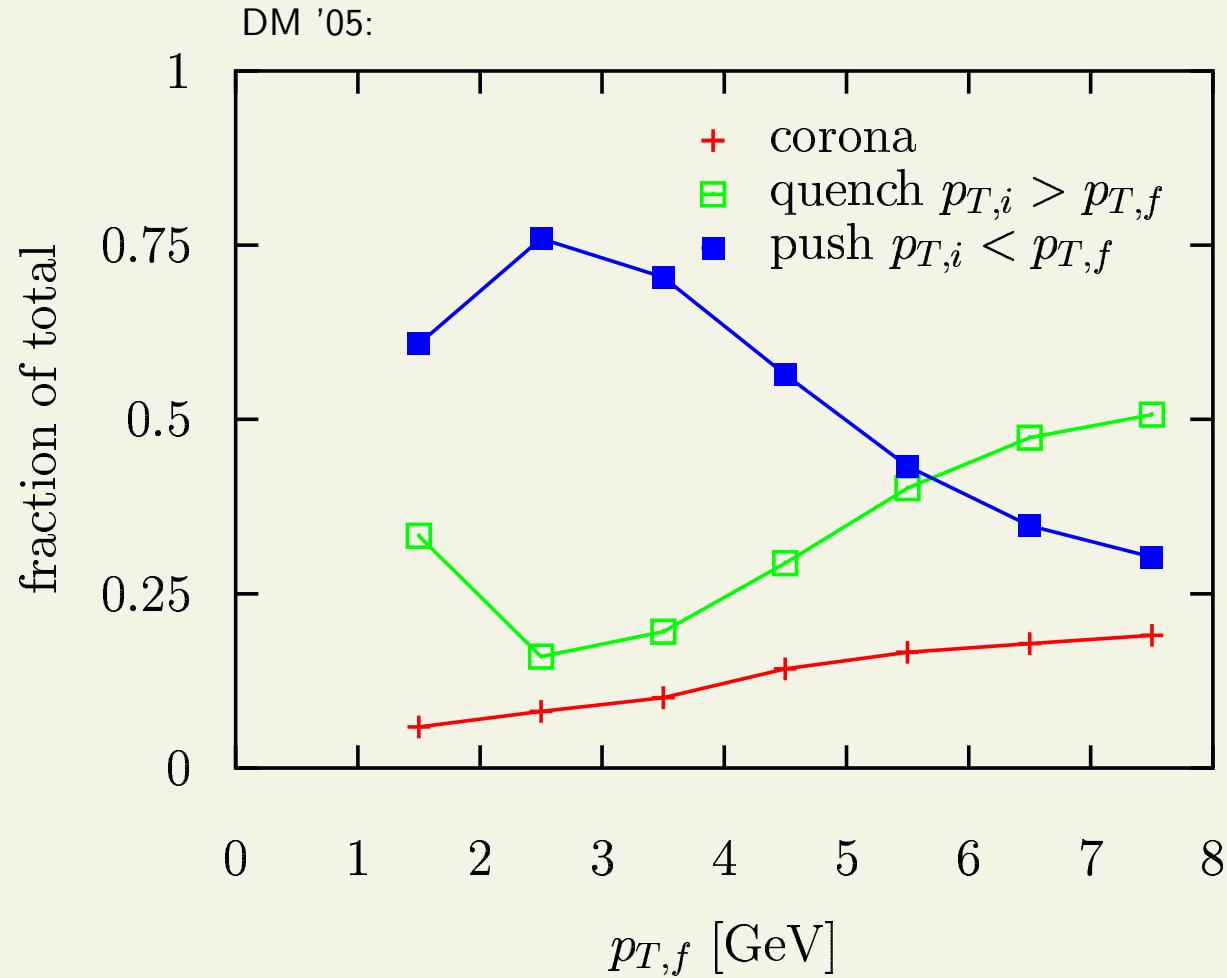
partons can end up with some **final parton momentum (p_T, y)** in three ways:

- escape with no interaction - **corona**
- interact and lose energy - **quench**
- **3rd possibility: interact and gain energy - “push”**

study relative importance vs pT in opaque plasma @ $6 \times$ perturbative opacities

MPC 1.8.0 w/ elastic and inelastic $2 \rightarrow 2$

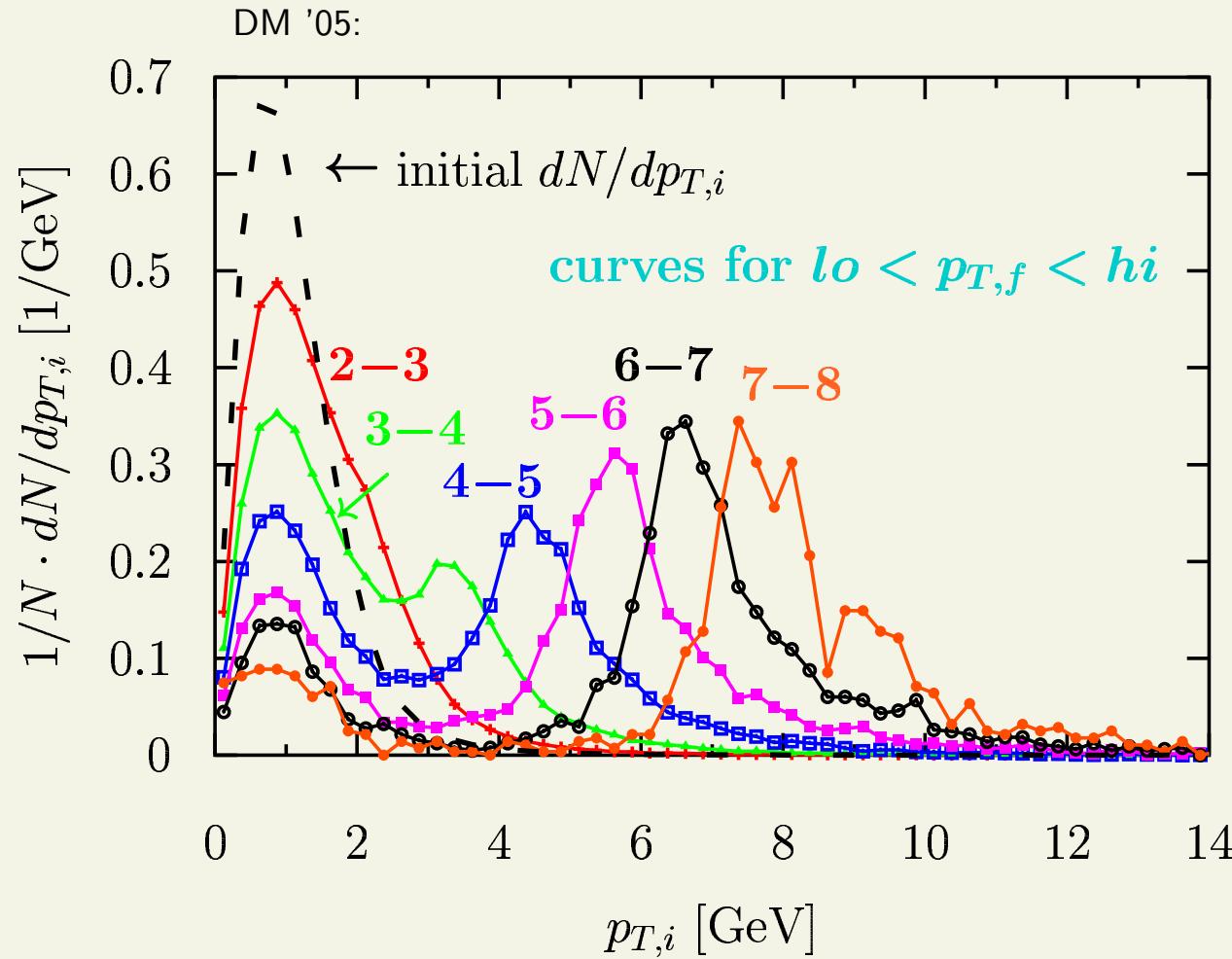
fractions from corona, quench, push vs pT, ($|y_f| < 1$)



corona and “push” are significant even at $p_{T,parton} \sim 8$ GeV

distribution of initial momenta for fixed final momentum bins, $|y_{fin}| < 1$

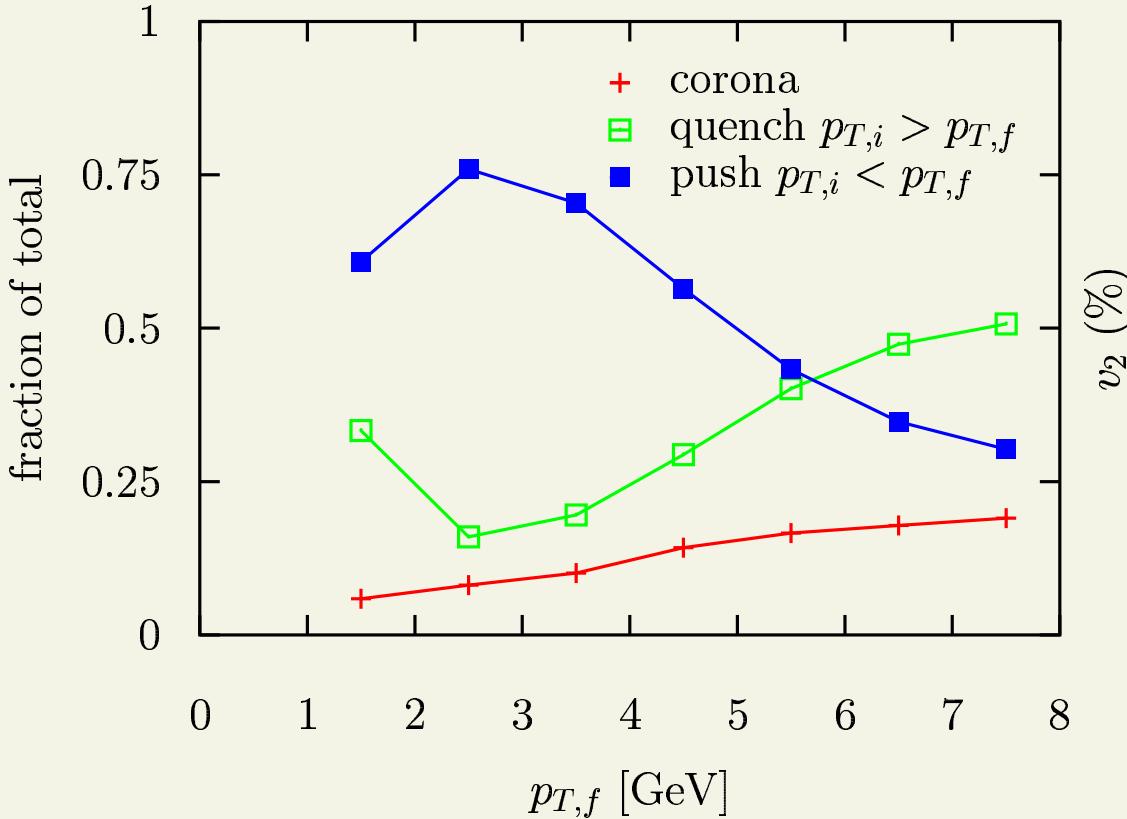
(only quench + “push” plotted, normalized)



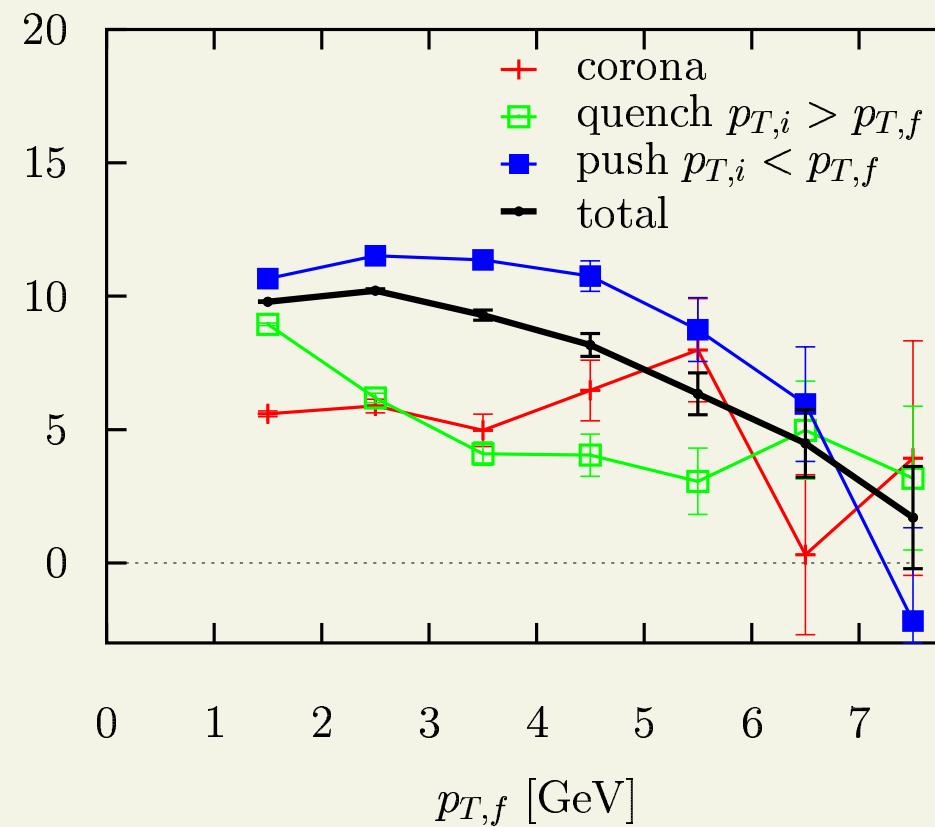
“lucky” $p_{T,i} \sim 1$ GeV soft partons can end up at $p_T \sim 7 - 8$ GeV

corona/quench/push fractions

DM '05:



elliptic flow contributions vs p_T

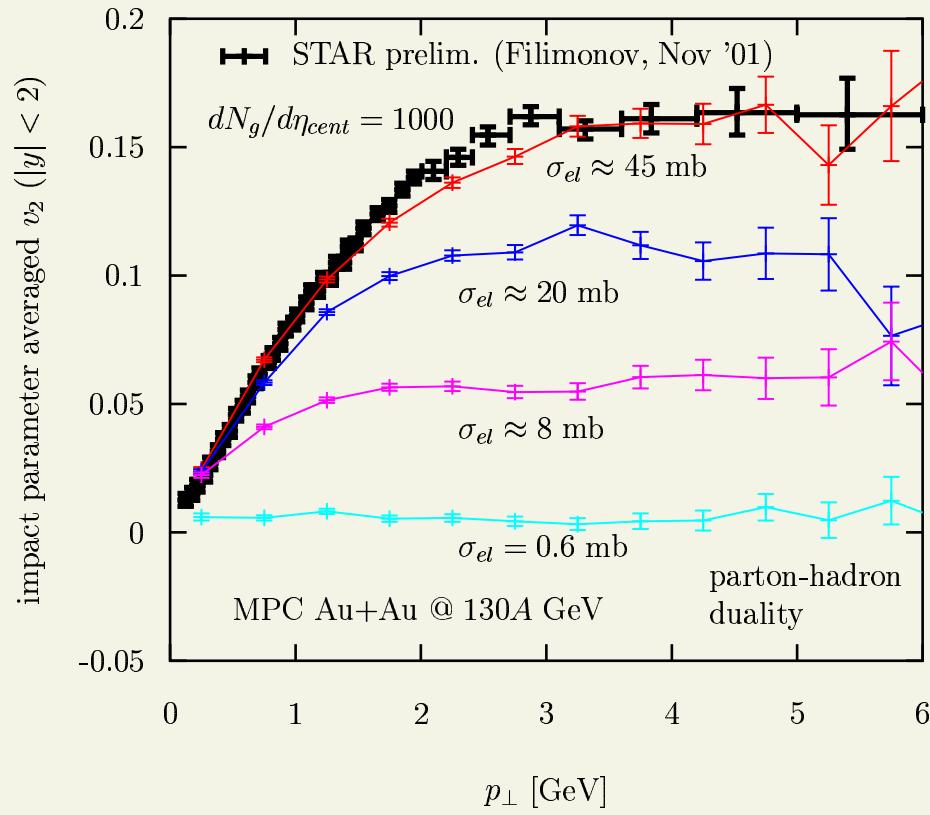


rapid v_2 drop from quench at high p_T is compensated by large v_2 of “pushed-up” partons

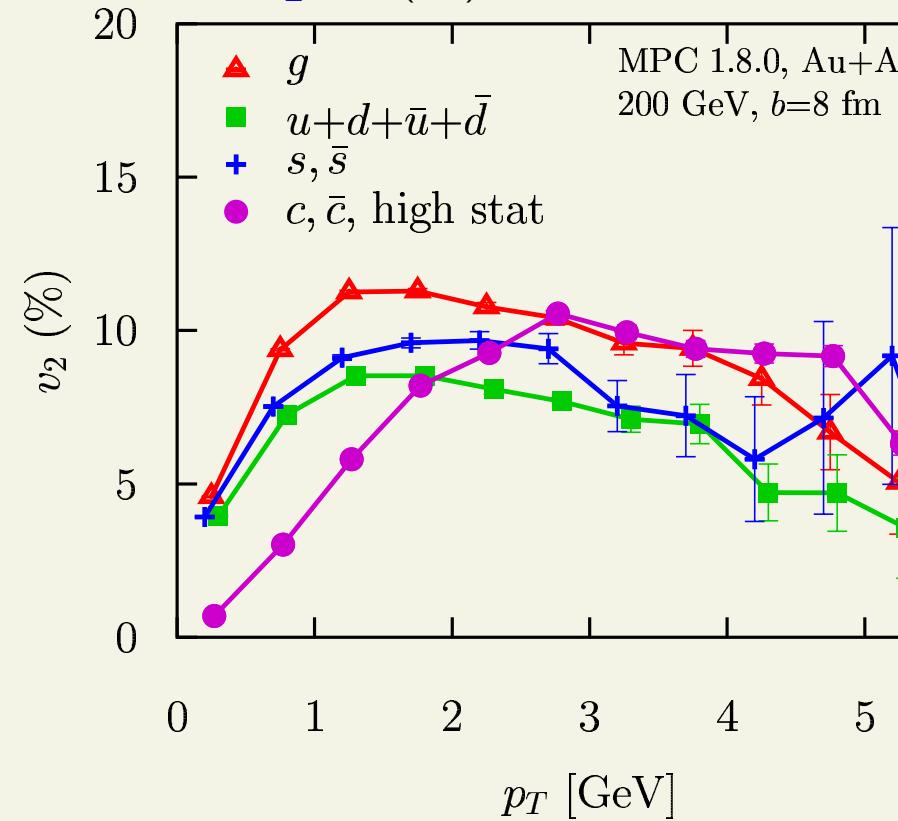
combined $v_2(p_T)$ still decreases at high p_T , but more slowly

"push" component is direct consequence of strongly-interacting plasma,
just like

large v_2 DM & Gyulassy, NPA 697 ('02):



or charm v_2 DM ('04):



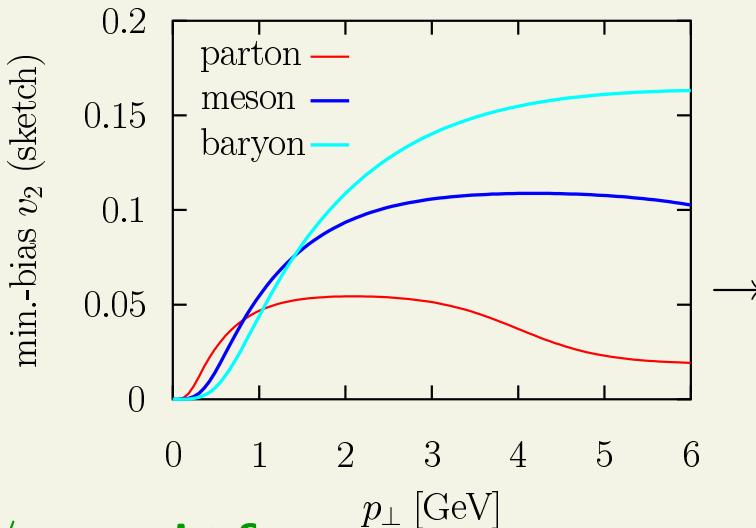
strong coupling should also enhance photon, lepton rates...

"Push" reaches beyond quark coalescence window $pT < 6$ GeV

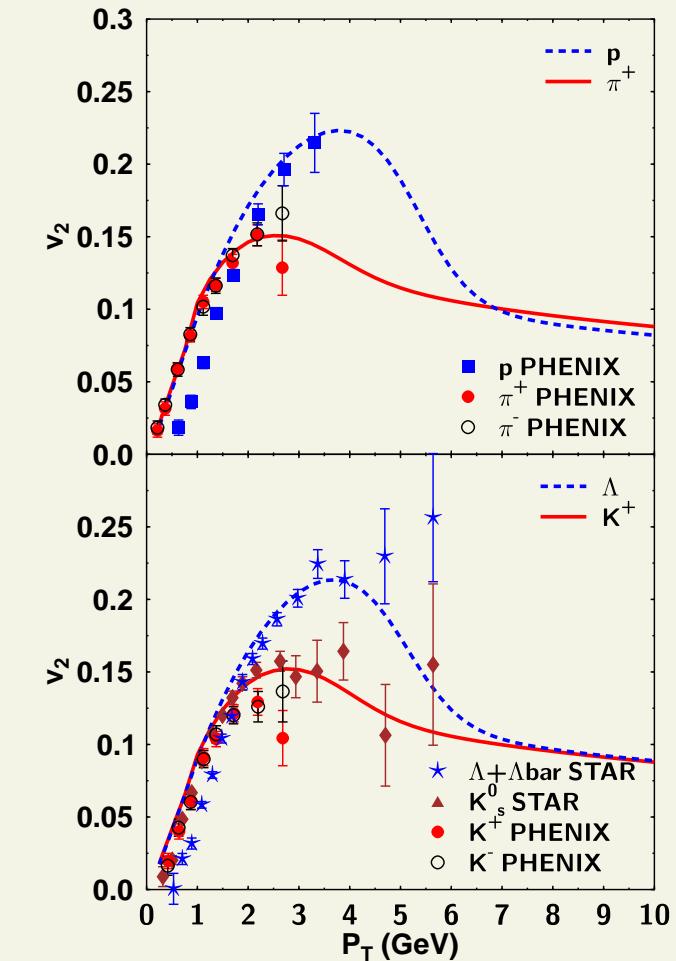
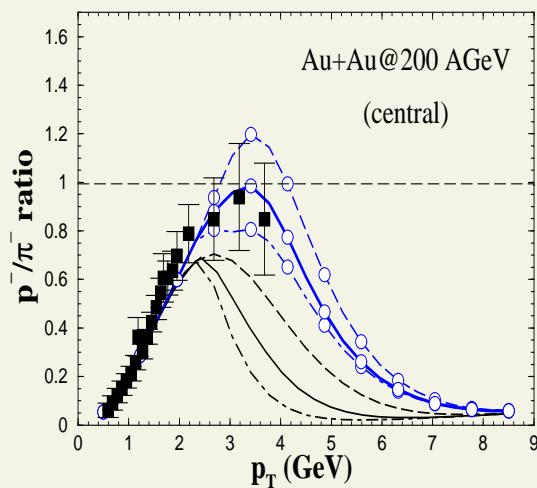
Ko, Lin, Voloshin, DM, Greco, Levai, Fries, Bass, ...

$$q\bar{q} \xrightarrow{\text{blue double arrow}} M \quad 3q \xrightarrow{\text{blue triple arrow}} B$$

v_2 , coal



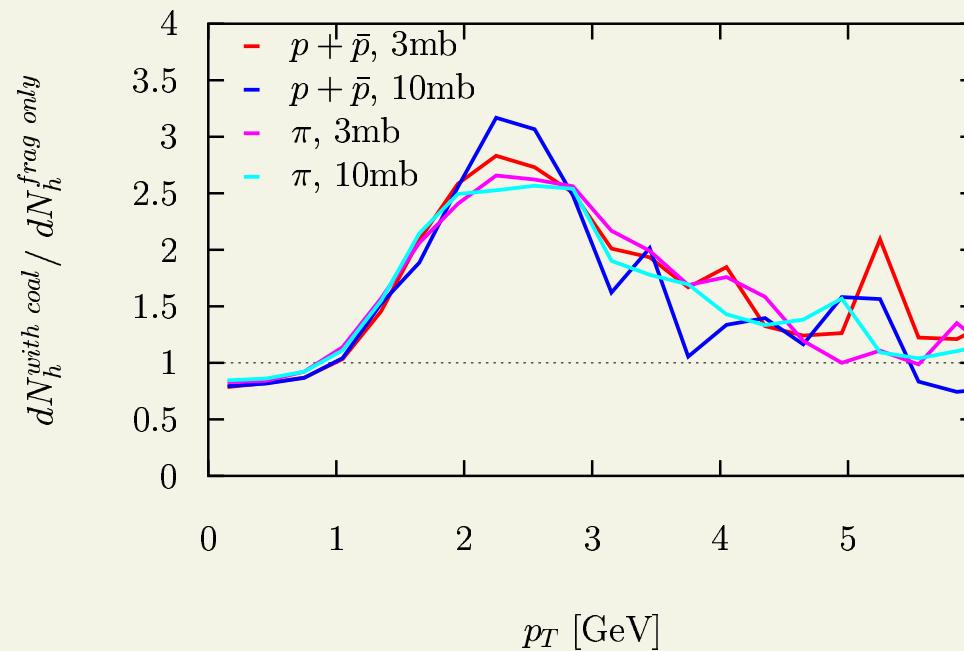
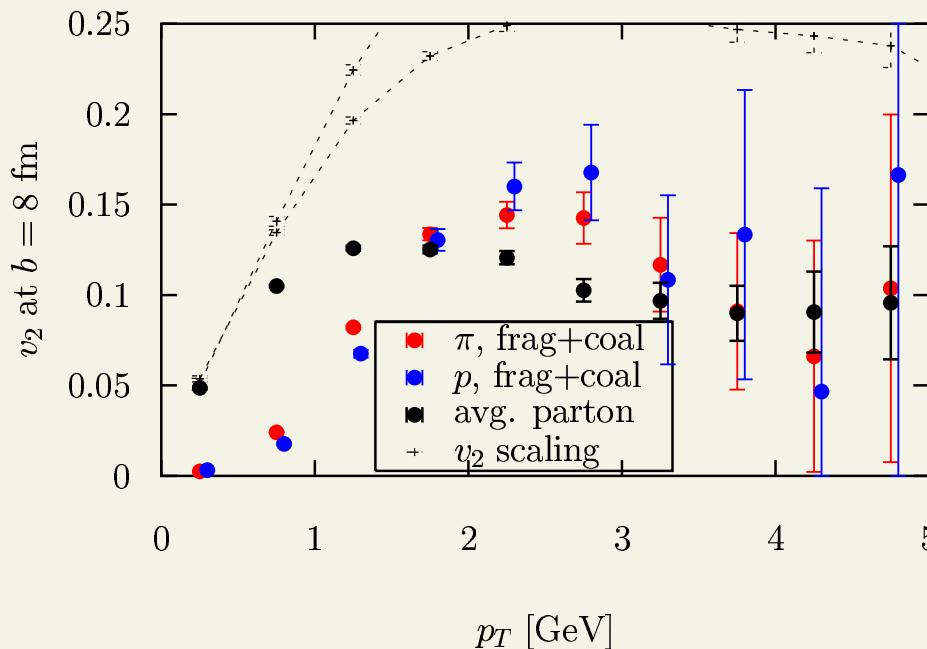
p/π , coal+frag



v_2 , coal+frag

– case of quark coalescence is still not settled —

DM ('04): **dynamical approach unsuccessful**



flow amplification greatly reduced, baryon-meson splitting mostly gone, p/π ratio unchanged

+ also hadron correlations - currently put in by hand...

- but for those only Lund string fragmentation works, not pQCD

Summary

- High pT observables inevitably depend on properties and spacetime evolution of the low- pT sector. This is good but also doubles challenge - need to treat everything together.
- "Nonperturbative" region could extend out to $pT \sim 10$ GeV at RHIC because a significant fraction of initially soft partons can migrate up to high pT in multiple scatterings.
- Many theoretical improvements needed, several puzzles remain. Need to invest more in theory at RHIC.